Boyle's Law in a Bottle

Pressure versus Volume

Introduction

In 1642 Evangelista Torricelli, who had worked as an assistant to Galileo, conducted a famous experiment demonstrating that the weight of air would support a column of mercury about 30 inches high in an inverted tube. Torricelli's experiment provided the first measurement of the invisible pressure of air. Robert Boyle, a "skeptical chemist" working in England, was inspired by Torricelli's experiment to measure the pressure of air when it was compressed or expanded. The results of Boyle's experiments were published in 1662 and became essentially the first gas law—a mathematical equation describing the relationship between the volume and pressure of air. What is Boyle's law and how can it be demonstrated?

Concepts

- Gas properties
- Pressure
- Boyle's law
- Kinetic-molecular theory

Background

Robert Boyle built a simple apparatus to measure the relationship between the pressure and volume of air. The apparatus consisted of a J-shaped tube that was sealed at one end and open to the atmosphere at the other end. A sample of air was trapped in the sealed end by pouring mercury into the tube (Figure 1). In the beginning of the experiment, the height of the mercury column was equal in the two sides of the tube. The pressure of the air trapped in the sealed end was equal to that of the surrounding air, equivalent to 29.9 inches (760 mm) of mercury. When Boyle added more mercury to the open end of the tube, the air trapped in the sealed end was compressed into a smaller volume (Figure 2). The difference in height of the two columns of mercury (Δh) was due to the additional pressure exerted by the compressed air compared to the surrounding air. Boyle found that when the volume of trapped air was reduced to one-half its original volume, the additional height of the column of mercury in the open end of the tube measured 29.9 inches. The pressure exerted by the compressed air was twice as great as atmospheric pressure. The mathematical relationship between the volume of the air and the pressure it exerts was confirmed through a series of measurements.

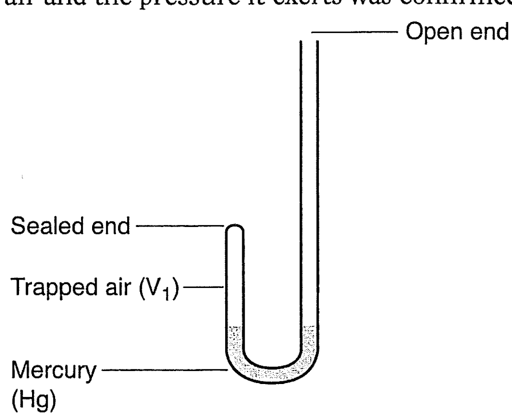

Figure 1.

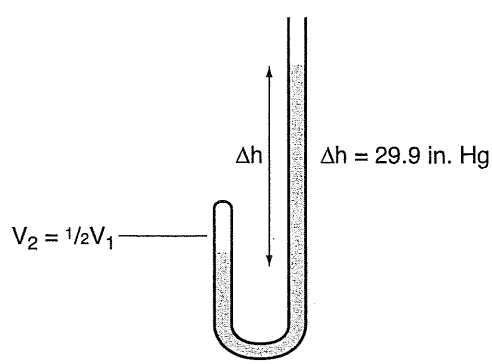

Figure 2.

Experiment Overview

The purpose of this experiment is to carry out a modern version of Boyle's classic experiment. The experiment will be carried out using air trapped inside a sealed syringe within a "pressure bottle." The bottle will be pressurized by pumping in air to obtain a pressure several times greater than that of the surrounding air. As some of the excess pressure within the bottle is then released, the volume of the trapped air inside the syringe will change. Volume measurements will be made at several different pressures and the results will be analyzed by graphing to derive the mathematical relationship between pressure and volume.

Pre-Lab Questions

1. According to our modern understanding of the gas laws, there are four measurable properties (variables) of a gas. These variables are P (pressure), V (volume), T (temperature), and n (number of moles). In Boyle's experiment, which two variables were held constant?

2. Fill in the blanks to summarize the relationship among the gas properties in Boyle's experiment: For a fixed ____________________ of gas at constant ____________________, the ______________________ of a gas increases as the _______________________ of its container decreases.

3. Pressure is defined in physics as force divided by area (P = force/area). According to the kinetic-molecular theory, the particles in a gas are constantly moving and colliding with the walls of their container. The pressure of the gas is related to the total force exerted by the individual collisions. Use the kinetic theory to explain the results of Boyle's experiment.

4. The pressure scale on a tire gauge is marked in units of pounds per square inch (psi). The scale starts at zero when the gauge is exposed to the surrounding air. This means that the total pressure is equal to the gauge pressure *plus* the pressure of the surrounding air. Standard atmospheric pressure (1 atm) is equal to 14.7 psi. Assume that you have just inflated the tire on your bicycle to 82 psi using a bicycle pump. What is the total pressure of air in the tire in psi? In atmospheres?

Materials

Bicycle pump with pressure gauge, or electric air pump

Pressure bottle, 1-L, with tire valve

Syringe, 10-mL, with syringe tip cap

Barometer (optional)

Graph paper

Tire gauge (optional)

Design of the Pressure Bottle

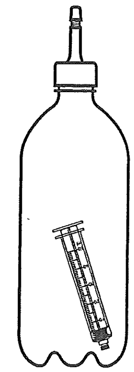

Figure 3.

The "pressure bottle" is a 1-L PETE (polyethylene terephthalate) soda bottle. The bottle cap has been fitted with a tire valve to give an airtight seal (Figure 3). Pumping air into the bottle using an ordinary bicycle pump makes it possible to pressurize the bottle above atmospheric pressure. The bottle retains its volume when it is pressurized—any expansion is negligible. The plastic used to make these bottles will withstand pressures up to about 100 psi.

Safety Precautions

The pressure bottle is safe if used properly. The bottle should not be inflated above 100 psi. Even if the bottle should explode, the plastic construction will only result in a quick release of air, an accompanying loud noise, and a hole in the bottle. The bottle will split but will not shatter. Wear eye protection (safety glasses or chemical splash goggles) when working with the pressure bottle.

Procedure

1. Using a barometer, measure the value of the local air pressure. *Note:* If a barometer is not available, consult an Internet site such as the national weather service site (http://weather.gov/) to obtain a current pressure reading for your area. Record the barometric pressure in the data table.
2. Obtain a 1-L pressure bottle and a 10-mL syringe with a rubber tip cap.
3. Press down on the brass pin in the tire valve fitted inside the bottle cap to release any excess pressure that may be inside the bottle. Remove the cap from the bottle.
4. Remove the tip cap from the syringe and pull on the plunger to draw about 9 mL of air into the syringe. Replace the tip cap to seal the air inside the syringe.
5. Place the sealed syringe inside a clean and dry, 1-L pressure bottle. Close the bottle with the special cap fitted with a tire valve. Tighten the cap securely.
6. Connect the tire valve to a bicycle pump or an electric air pump. *Note:* Exercise caution if using an electric air pump. Do not exceed the maximum suggested pressure.
7. Pump air into the pressure bottle to obtain a pressure reading of 50–60 psi on the tire gauge. Do NOT exceed 100 psi. *Note:* Using a manual pump is a safety feature—it is very difficult to pump more than about 70 psi into the pressure bottle by hand.
8. Loosen the connection between the pressure bottle–tire valve and the pump to release a small amount of pressure. As soon as you see the syringe plunger start to move, immediately retighten the tire valve to the pump.
9. Using the pump gauge, measure and record the pressure to within ±1 psi.

10. Measure and record the volume of air trapped in the syringe at this bottle pressure. *Note:* Measure the volume at the black rubber seal, not at the inverted V-like projection (see Figure 4). The syringe barrel has major scale divisions marked every milliliter, and minor scale divisions every 0.2 mL. The volume should be estimated to within ±0.1 mL.

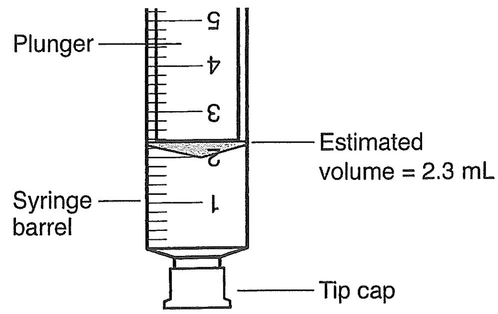

Figure 4.

11. Loosen the connection between the pressure bottle–tire valve and the bicycle pump to release a small amount of pressure from the pressure bottle. Try to reduce the pressure by no more than about 10 psi. Immediately retighten the tire valve to the pump.

12. Measure both the new pressure on the pump gauge and the new volume of the air trapped inside the syringe. Record all data in the data table. *Note:* If you are using a tire gauge to measure pressure, press lightly on the brass pin in the tire valve to release some air pressure. It may be necessary to bleed off enough air initially to get the first pressure reading below 50 psi, which is the scale maximum on many tire gauges.

13. Repeat steps 11 and 12 to measure the volume of gas trapped in the syringe at several different pressures down to about 5 psi. It should be possible to obtain at least 5–6 pressure and volume measurements in this range.

14. When the pressure on the tire gauge measures close to zero, remove the tire valve from the pump. Press down on the brass pin inside the tire valve to release all of the excess pressure within the pressure bottle. Record the final volume of air in the syringe at atmospheric pressure.

15. If time permits, repeat steps 7–14 to obtain a second, independent set of pressure–volume data. Record this data as Trial 2 in the data table.

Name: ______________________________

Class/Lab Period: ______________________________

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Data and Results Table

Barometric Pressure							
Trial 1				Trial 2			
Gauge Pressure	Volume of Air in Syringe	Total Pressure*	1/V†	Gauge Pressure	Volume of Air in Syringe	Total Pressure*	1/V†

*See Post-Lab Question #2. †See Post-Lab Question #5.

Post-Lab Questions *(Use a separate sheet of paper to answer the following questions.)*

1. Convert the local barometric pressure to psi units and enter the value to the nearest psi in the Data and Results Table. Some appropriate conversion factors are shown below.

   1 atm = 760 mm Hg = 29.92 in Hg = 14.7 psi

2. The pressure gauge measures the relative pressure in psi above atmospheric pressure. For each pressure reading in the Data and Results Table, add the local barometric pressure to the gauge pressure to determine the total pressure of air inside the pressure bottle. Enter the total pressure to the nearest psi in the table.

3. Plot a graph of volume on the y-axis versus total pressure on the x-axis. *Note:* The origin of the graph should be 0,0. Choose a suitable scale for each axis so that the data points fill the graph as completely as possible. Remember to label each axis and give the graph a title.

4. Describe the shape of the graph. Draw a best-fit straight or curved line, whichever seems appropriate, to illustrate how the volume of a gas changes as the pressure changes.

5. The relationship between pressure and volume is called an "inverse" relationship—the pressure increases as the volume of air trapped in the syringe decreases. This inverse relationship may be expressed mathematically as $P \propto 1/V$. Calculate the value of $1/V$ for each volume measurement and enter the results in the Data and Results Table.

6. Plot a graph of pressure on the y-axis versus $1/V$ on the x-axis and draw a best-fit straight line through the data. *Note:* The origin of the graph should be 0,0. Choose a suitable scale for each axis so that the data points fill the graph as completely as possible.

7. Another way of expressing an inverse relationship between two variables ($P \propto 1/V$) is to say that the mathematical product of the two variables is a constant ($P \times V =$ constant). Multiply the total pressure (P) times the volume (V) for each set of data points. Construct a Results Table to summarize the $P \times V$ values.

8. Calculate the average value of the $P \times V$ "constant" and the average deviation. What is the relative percent error (uncertainty) in this constant?

$$\text{Relative percent error} = (\text{Average deviation/Average value}) \times 100\%$$

9. At constant temperature, the pressure of a gas is proportional to the concentration of gas particles in the container. When some of the pressure was released from the bottle, the syringe plunger moved up. Why did this happen? Use diagrams and explain in words what happens to the gas particles moving around both inside and outside the syringe before and after the pressure is released.

10. *(Optional)* Look up the properties of PETE on the Internet. What characteristics of PETE make it an ideal plastic for use in soda bottles?